A Simulation on the Regeneration of Activated Carbon with an Indirect Heating Method

DOI: 10.15255/KUI.2016.021
KUI-31/2016
Original scientific paper
Received May 4, 2016
Accepted August 2, 2016

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Abstract

It is of great challenge and significance to recycle activated carbon (AC), yet still with various problems in operation. Here, we have performed a simulation on the regeneration of AC by using an indirect heating method with an unsteady cylindrical heat transfer model. The result has shown that the optimal parameters for a regeneration tube of outer diameter $\Phi = 108$ with wall thickness 4 mm were: heating in the tube for 30 min at a surrounding temperature of 550 °C. In these conditions, a temperature of 417.5 °C could be obtained at the centre of the cylindrical tube, reaching the temperature required for AC regeneration. The experimental values obtained in our laboratory were consistent with the simulation, providing significant references for scaling up pilot plant of AC regeneration.

Keywords

Activated carbon, regeneration, indirect heating, unsteady heat transfer

1. Introduction

With the improvement of regulations for environmental protection and the increasing expenditures for pollution control, China will be in the lead in application of activated carbon (AC). Highly porous carbonaceous materials are referred to as activated carbons that are applied in various fields owing to extraordinary characteristics.[1,2] The features of these materials are large surface area, microporous and mesoporous structures, and versatile adsorption capacity for different heavy metal ions. Thereby, they can be applied as ideal adsorbents in many types of water purification systems. Because the pore dimensions of ACs are more or less close to the size of the adsorbate molecules, they exhibit high adsorption capacity.[2–4] AC has become a suitable adsorbent for wastewater treatment in the last decades.

It is wasteful to use disposable AC due to its high pricing. Therefore, it is of great challenge and significance to restore the adsorption performance of AC by removing the adsorbates in its micropores with physical or chemical methods. Various approaches have been proposed to regenerate AC,[5] such as heating at elevated temperatures,[6] electric heating,[7] wet oxidation,[8] solvent regeneration,[9] forced discharging,[10] microwave regeneration,[11] *etc*. However, only the first one could meet the needs of large-scale production. To date, high temperature heating usually depends on the conductivity of AC or direct heating by hot blast heater for regeneration. The former has disadvantages, such as low conductivity of AC, difficulty in controlling the operating conditions, high power consumption, *etc*., whereas the latter process has an intrinsic disadvantage that oxygen in hot blast can easily lead to ashing of AC or even high ablation rate caused by spontaneous combustion.

Schlunder[12] proposed the concept of "convective heat transfer of particles" to describe the heat transfer process with particles. The heat conduction between contact surfaces will dominate while the particle size is small, which is analogous to the heat transfer between continuous fluids. This conception can apply to the heat transfer process of AC particles. And a variety of models as well as related equations have been proposed.

Natarajan and Hunt[13] studied the effect of shearing on the convective heat transferring from a heater immersed in a vertical granular flow in a channel. This model investigated the effect of particles microstructure on the heat transfer process. However, the calculation was redundant and difficult for engineering design.

Molerus[14] investigated the contact resistance for the heat transferring between adjacent rough particles in moving bed, and elicited a model for qualitatively accounting for the short time heat transfer, as well as steady-state heat conduction in particle beds. However, relatively large errors were usually observed for unsteady state heat transfer.

Nozad et al.[15,16] studied the heat transfer process with particles by effective medium approach (EMA). Specifically, according to the assumption of effective medium, the macro properties of the system as well as its transfer process would be connected with the microstructure and micro transfer features of the system, via replacing particles system by an isotropically homogeneous, effective medium. To obtain the distribution of the mean temperature of the particle flow, statistical averaging, and empirical correlation

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were applied to simplify the microstructure (composition, voidage, and texture) of the materials. This approach could be a useful reference to study the unsteady heat transfer of regenerative feed heating systems, because it is easy to use and convenient for engineering design.

Our preliminary experiments proved that indirect heating was better than direct heating in retaining the performance of AC. For example, we could retain 97 % or higher strength of AC, 95 % or higher recovery of adsorption capacity, and 0.5 % or less ashing rate for more than ten cycles with indirect heating on AC. On the contrary, the ashing rate was higher than 2 % when using direct heating, which had adverse effects on further use of AC. However, regeneration with indirect heating is a process of heating and heat transfer between solid interfaces, and a process of unsteady heat transfer. In this paper, we used EMA and nomographic method to simulate the indirect heating process. The result was consistent with the experimental values previously obtained in our laboratory, indicating that the method could provide meaningful references for related industries.

2. Experimental

As shown in Fig. 1, the heating furnace for AC regeneration is composed of a heating and a cooling chamber, a metallic regeneration tube, a stock feeding and discharging device.

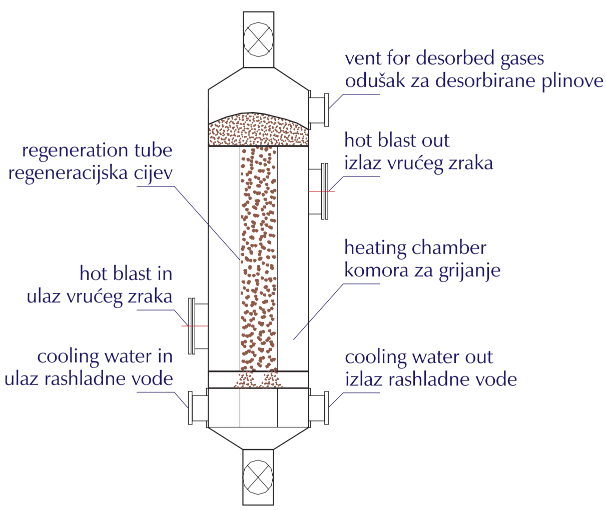

Fig. 1 – Heating furnace for AC regeneration
Slika 1 – Toplinska peć za regeneraciju AC-a

The saturated AC was fed and moved slowly top-down in the metallic regeneration tube. The tube with AC was heated to a temperature higher than 400 °C in the heating chamber. Harmful gases were desorbed from AC surface and sucked for recycling under negative pressure. The AC was then re-activated after desorption and returned to use after cooling and discharging.

3. Results and discussion

The major calculation methods for unsteady state heat transfer were analytical,[17] lumped parameterizing and nomographic method,[18] *etc*. The former two methods not only require the eigenvalue traced by Biot number, but also involve redundant calculation using Bessel function, and so on, which are inconvenient for engineering design. The nomographic method is easy to use for engineers, owing to its simplified calculation process. Therefore, in this study, we applied the nomographic method to the design and calculation of the regeneration of AC. The basic methodology and procedure are described below.

3.1 Process of heat regeneration of AC can be simplified as an unsteady heat transfer model of a cylinder

To ensure the complete regeneration of AC and still avoid excessive loss from overtemperature, the temperature of the regeneration tube should be maintained at around 550 °C.[5,19] The AC gradually absorbs the heat from the surroundings when moving down in the regeneration tube, increasing its temperature to reach that required for regeneration. Since AC is a poor thermal conductor and the heating source of regeneration is from the outside combustor, the radial heat transfer was mainly considered while ignoring the axial transfer in the calculation. We can use the effective medium approach (EMA) for convenient calculation, and choose an AC column (AC cylinder) with a unit length as the objective. Then the heat absorbing process for regeneration of AC could be simplified as a problem of unsteady heat transfer of the AC cylinder at a constant temperature, by the assumption that AC is isotropically homogeneous.

3.2 Biot number and the Fourier number

The Biot number (*Bi*) and the Fourier number (*Fo*) are required for the calculation of unsteady heat transfer of a cylinder with a graphical method. *Bi* and *Fo* are estimated using Eqs. (1)–(2):

$$Bi = \frac{h\,\delta}{\lambda_{AC}} \tag{1}$$

$$Fo = \frac{\alpha\, t_{heating}}{\delta^2} \tag{2}$$

where h is the heat transfer coefficient between AC and the surroundings, which is assumed to be 50 $W\,m^{-2}\,K^{-1}$ according to our preliminary experiments in the laboratory, λ_{AC} is the thermal conductivity[20] and is assumed to be 0.25 $W\,m^{-1}\,K^{-1}$ in this study; δ is the design size, whose value is half of the thickness and the radius for an infinite plate and a cylinder, respectively. In this study, the regeneration tube is a seamless steel pipe of $\Phi = 108$ mm with wall thickness 4 mm, and thus the inner radius of the tube (δ) is 0.05 m, as calculated in Eq. (3):

$$\delta = \frac{108\ \text{mm} - 2 \cdot 4\ \text{mm}}{2} = 50\ \text{mm} = 0.05\ \text{m} \tag{3}$$

In Eq. (2), $t_{heating}$ is the heating time, which is usually set to an initial value of 1200 s, and α is the thermal diffusivity, as calculated in Eq. (4):

$$\alpha = \frac{\lambda_{AC}}{\rho_{AC}\, c_{AC}} \tag{4}$$

where ρ_{AC} is the bulk density of AC, ranging from 300 to 650 kg m^{-3} and a value of 500 kg m^{-3} was applied in this study, and c_{AC} is the specific heat capacity of AC and was taken as 840 J kg^{-1} K^{-1} in this study. As a result, α was calculated to be $4.67 \cdot 10^{-7}$ m^2 s^{-1} according to Eq. (4).

Consequently, based on Eqs. (1) to (4), *Bi* and *Fo* were calculated to be 12.5 and 0.2286, respectively. Then 1/*Bi* is equal to 0.08.

3.3 Temperature at the centre of AC cylinder

The temperature at the centre of AC cylinder can then be found from nomographic charts of temperature based on the Biot number and the Fourier number. Figs. 2 and 3 are the dimensionless nomographic charts of temperature at the centre of a cylinder during the process of unsteady heat transfer, which are usually called normalized graphs. Based on *Fo* and 1/*Bi*, the ratio of θ_m/θ_0 (the dimensionless central temperature) can then be found to be 0.35 (Fig. 2), where θ_m is the temperature at the centre of AC layer, and θ_0 the difference between the initial temperature of AC layer (θ_{ini}) and the surrounding temperature (θ_e). This temperature difference is 530 °C for θ_{ini} = 20 °C, and θ_e = 550 °C.

After that, the ratio of θ/θ_m can be found from Fig. 3 based on 1/*Bi* and *r*/*R*, where θ is the temperature at any point of the AC cylinder, *r* and *R* are the radial distances from that point to the central shaft and the radius of the cylinder, respectively.

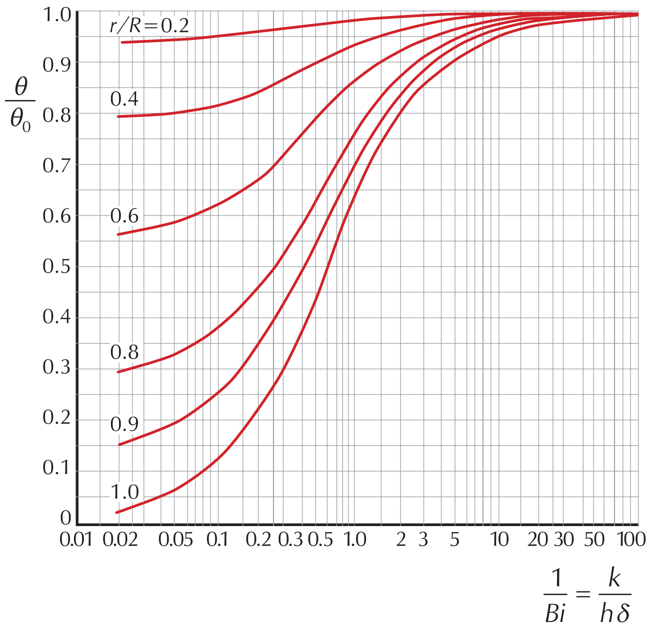

Fig. 3 – Nomographic chart of temperature at any point of the cylinder
Slika 3 – Nomogram temperature u bilo kojoj točki cilindra

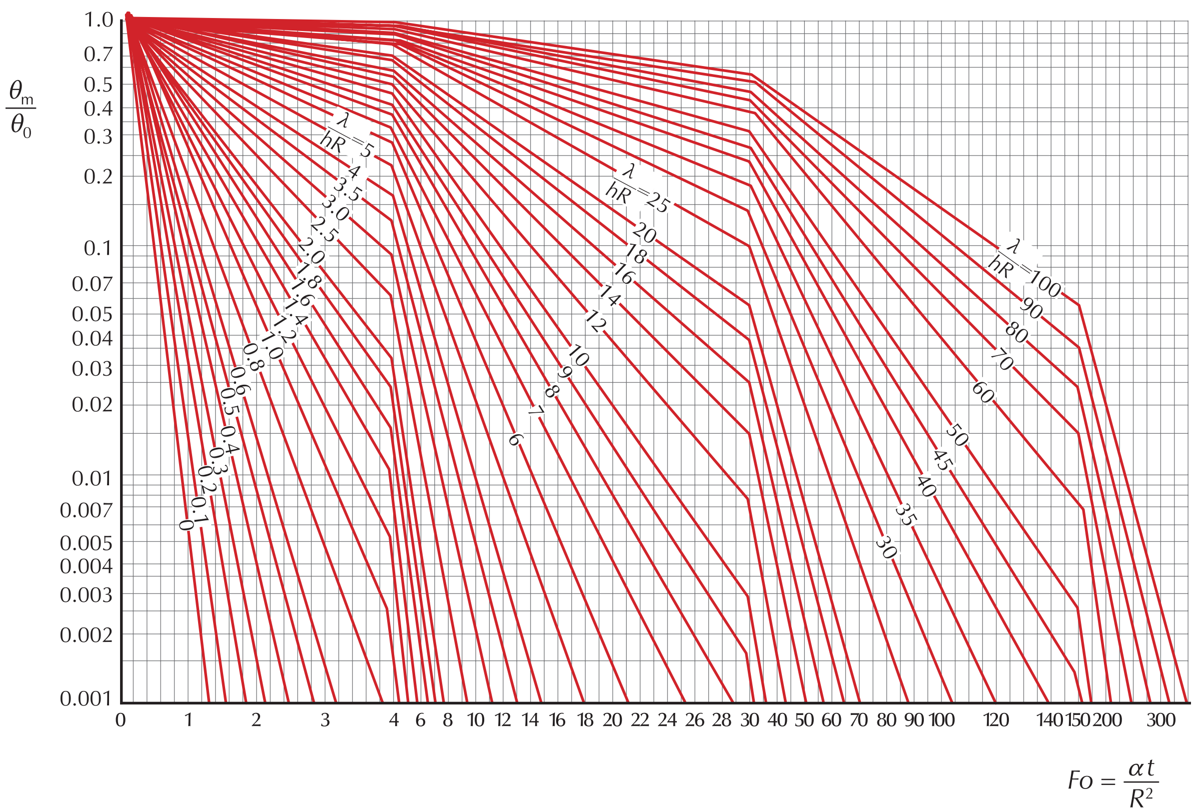

Fig. 2 – Nomographic chart of temperature at the centre of the cylinder
Slika 2 – Nomogram temperature u središtu cilindra

Since the heat transfer for AC regeneration is from the outside in, the lowest temperature is certainly found at the central part of the AC cylinder. As long as the central temperature reaches that for AC regeneration, the temperature of the whole AC cylinder could definitely meet the requirements. On the other hand, the ratio of r/R is zero at the centre of the AC cylinder; the corresponding ratio of θ/θ_m is then equal to 1.0 regardless of the value of $1/Bi$ (Fig. 3). Thus, the ratio of θ/θ_0 was then obtained from Eq. (5):

$$\frac{\theta}{\theta_0} = \left(\frac{\theta}{\theta_m}\right) \cdot \left(\frac{\theta_m}{\theta_0}\right) = 1 \times 0.35 = 0.35 \qquad (5)$$

The core temperature (θ_{centre}) can then be deduced from Eq. (6):

$$\theta_{centre} = \left(\frac{\theta}{\theta_0}\right) \cdot \theta_0 + \theta_e = 0.35 \times (-530) + 550 = 364.5 \text{ °C} \qquad (6)$$

That is to say, for AC in a regeneration tube of $\Phi = 108$ mm with wall thickness 4 mm with an initial temperature of 20 °C and a surrounding temperature of 550 °C, the core temperature can only reach 364.5 °C within 20 min, which is insufficient for AC regeneration (400 °C).

Therefore, a re-calculation should be performed with the heating time reset. For a reset heating time of 1800 s, a similar procedure as above resulted in a Fo value of 0.3428. Based on Fig. 2, the ratio of θ_m/θ_0 can then be found to be 0.25. The ratio of θ/θ_0 was the same (*i.e.* 0.25) according to Fig. 3. That yields a core temperature (θ_{centre}) of 417.5 °C, which is sufficiently high for AC regeneration. In summary, under a surrounding temperature of 550 °C, AC in a regeneration tube of $\Phi = 108$ mm with wall thickness 4 mm should stay for at least 30 minutes to allow the core temperature to reach that required for regeneration.

We also selected a regeneration tube of $\Phi = 168$ mm with wall thickness 6 mm for comparison. For a heating time of 30 min, the finally obtained value of θ_{centre} was 126 °C. It is obvious that the core temperature would only be 126 °C in a heating time of 30 minutes if an oversized regeneration tube is selected, far less than 400 °C. These results suggested that the heating time for AC in a tube to reach the temperature required for regeneration increases with increasing the diameter of the tube, which is unfavourable for large-scale industrial operation. This is attributed to the fact that AC is a poor thermal conductor; and a longer time is required for heat transfer to the centre of the tube with increasing the diameter. However, an undersized one could easily cause blocking because of the "bridging" effect between AC particles in the tube. As a result, we recommend a regeneration tube with a diameter of around $\Phi = 100$ mm.

3.4 Calculation of heat transfer

The heat transferred to the AC cylinder can also be obtained from nomographic chart of heat based on the Biot number and the Fourier number. The dimensionless nomographic chart of heat for a cylinder during the process of unsteady heat transfer is shown in Fig. 4, where Q refers to the heat absorbed per length of AC column during a period of 30 min, and Q_0 refers to the heat absorbed per length of AC column for its temperature increasing from the initial temperature θ_{ini} to the surrounding temperature θ_e; q is the heat absorbed per mass of AC during the time of 30 minutes.

First, the value of $Fo\,Bi^2$ was calculated.

$$Fo\,Bi^2 = 0.3428 \times 12.52 = 53.57 \qquad (6a)$$

And then, based on $Fo\,Bi^2$ and Bi, the value of Q/Q_0 can be found to be 0.75 from Fig. 4. Q_0 is calculated according to Eq. (7):

$$Q_0 = \pi R^2 \rho_{AC}\, c_{AC} \left(\theta_e - \theta_{ini}\right) = 1\,748\,300.4 \text{ J m}^{-1} \qquad (7)$$

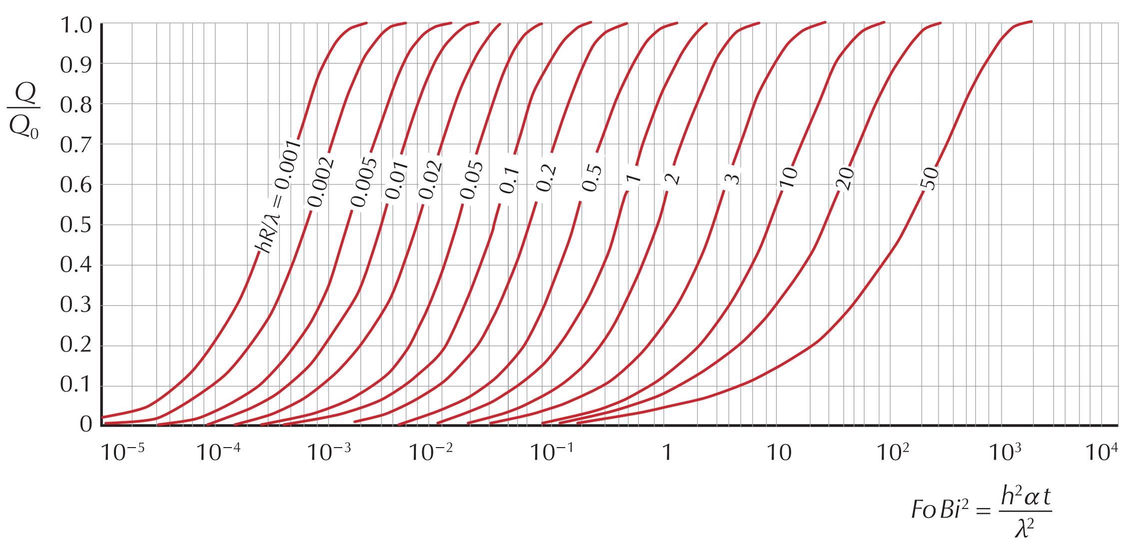

Fig. 4 – Nomographic chart of heat for a cylinder during the process of unsteady heat transfer
Slika 4 – Nomogram topline cilindra tijekom procesa nestacionarnog prijenosa topline

Q and q are estimated by using Eqs. (8) and (9).

$$Q = \left(\frac{Q}{Q_0}\right) Q_0 = \\ = 0.75 \times 1\,748\ 300.4\ \text{J m}^{-1} = 1\,311\ 225.3\ \text{J m}^{-1} \quad (8)$$

$$q = \frac{Q}{\rho_{AC}\, \pi R^2} = \frac{1\,311\ 225.3}{500 \times 3.14 \times 0.05^2}\ \text{J kg}^{-1} = 333.9\ \text{kJ kg}^{-1} \quad (9)$$

The experimental testing of AC regeneration conducted in our laboratory showed that, under a surrounding temperature of 550 °C, the core temperature of AC in the regeneration tube was about 422 °C during a heating time of 30 minutes, which is in very good agreement with the calculation.

4 Conclusion

The heat absorbing process for regeneration of AC could be simplified as a problem of unsteady heat transfer of the AC cylinder at a constant temperature. Based on the EMA of particle heat transfer model, we analysed the indirect heating reactivation process of AC particles and then we made the calculation of regeneration tube.

The diameter of AC regeneration tube is critical to the regeneration by using a heating furnace. The heating time for AC in a tube to reach the temperature required for regeneration increases with increasing the diameter of the tube, which is unfavourable for large-scale industrial operation. However, an undersized tube could easily cause blocking because of the "bridging" effect between AC particles. According to our calculation and experimental testing, a regeneration tube with a diameter of around $\Phi = 100$ mm was recommended. With a regeneration tube of this size and a surrounding temperature of 550 °C, the core temperature of AC could reach 400 °C or higher during a heating time of 30 minutes in the tube, which is sufficient for AC regeneration. The results of this study could provide meaningful references for related industries of AC regeneration.

List of symbols and abbreviations
Popis simbola i kratica

AC – activated carbon
– aktivni ugljen

EMA – effective medium approach
– teorija efektivnog medija

Bi – Biot number
– Biotov broj

c_{AC} – specific heat capacity of AC, J kg^{-1} K^{-1}
– specifični toplinski kapacitet AC-a, J kg^{-1} K^{-1}

Fo – Fourier number
– Fourierov broj

h – heat transfer coefficient, W m^{-2} K^{-1}
– koeficijent toplinske provodnosti, W m^{-2} K^{-1}

Q – heat absorbed per length of AC column during a period of 30 minutes, J
– dovedena toplina po duljini stupca AC-a tijekom 30 minuta, J

Q_0 – heat absorbed per length of AC column for temperature increase $\theta_e - \theta_{ini}$, J
– dovedena toplina po duljini stupca AC-a za porast temperature $\theta_e - \theta_{ini}$, J

q – heat absorbed per mass of AC during the time of 30 minutes, J
– dovedena toplina po masi AC-a tijekom 30 minuta, J

R – radius of the cylinder
– polumjer cilindra

r – radial distance from the central shaft
– udaljenost od osi cilindra

$t_{heating}$ – heating time, s
– vrijeme zagrijavanja, s

α – thermal diffusivity, m^2 s^{-1}
– toplinska difuzivnost, m^2 s^{-1}

δ – characteristic dimension, inner radius of the tube, m, mm
– karakteristična dimenzija, unutarnji polumjer cijevi, m, mm

θ_0 difference between the initial temperature of AC layer (θ_{ini}) and the surrounding temperature (θ_e), °C
razlika između početne temperature AC-a (θ_{ini}) i okolne temperature (θ_e), °C

θ_{centre} – core temperature, °C
– temperatura jezgre, °C

θ_e – surrounding temperature, °C
– okolna temperatura, °C

θ_{ini} – initial temperature of AC layer, °C
– početna temperatura sloja AC-a, °C

θ_m – the temperature at the centre of AC layer, °C
– temperatura u središtu sloja AC-a, °C

λ_{AC} – thermal conductivity, W m^{-1} K^{-1}
– toplinska provodnost, W m^{-1} K^{-1}

ρ_{AC} – bulk density of AC, kg m^{-3}
– nasipna gustoća AC-a, kg m^{-3}

Φ – outer diameter of the tube, mm
– vanjski promjer cijevi, mm

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SAŽETAK

Simulacija regeneracije aktivnog ugljena neizravnim grijanjem

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Recikliranje aktivnog ugljena (AC) iznimno je važno i interesantno, no još se uvijek javljaju različiti problemi u provedbi postupka. U ovom radu simulirana je regeneracija AC-a neizravnim grijanjem primjenom nestacionarnog cilindričnog modela prijenosa topline. Za regeneracijsku cijev vanjskog promjera 108 mm i debljine stjenke 4 mm optimalno je grijanje 30 min pri okolnoj temperaturi 550 °C. U tim uvjetima temperatura 417,5 °C može se postići u središtu cilindrične cijevi čime je dosegnuta temperatura potrebna za regeneraciju AC-a. Eksperimentalne vrijednosti dobivene u laboratoriju bile su u skladu sa simulacijom, čime su dobivene važne referencije za postupno uvećanje pilotnog postrojenja regeneracije AC-a.

Ključne riječi
Aktivni ugljen, regeneracija, neizravno grijanje, nestacionarni prijenos topline

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Izvorni znanstveni rad
Prispjelo 4. svibnja 2016.
Prihvaćeno 2. kolovoza 2016.